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Yrast levels in ^{44}Ti

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The reaction ^{32}S(^{14}N, $p n \gamma$)^{44}Ti has been studied with a view to populating high spin states in ^{44}Ti. In singles and γ-γ coincidence experiments γ-ray transitions in the ground state band and a negative parity band are seen and three levels connected to the ground state band, at 6508, 7671, and 8040 keV, are inferred. Angular distributions are consistent with stretched cascades. The lifetime of the 7671-keV level, presumed 10^+, has been determined by the attenuated Doppler-shift method to be 2.7 ± 0.5 ps. A comparison of the present reaction with the recently reported ^{28}Si(^{19}F, $p2n\gamma$)^{44}Ti reaction is made and a method for predicting the propensity of these types of reaction to feed high spin states is proposed. An $(fp)^4$ shell model calculation of yrast levels up to $J = 12$ has been made.

[NUCLEAR REACTIONS ^{32}S(^{14}N, $pn\gamma$), E=26–43 MeV; measured γ-γ coin and $\sigma(E)$; ^{44}Ti deduced levels; measured $W(\theta_\gamma)$, Doppler-shift attenuation; deduced J^π, $T_{1/2}$. Natural targets, Ge(Li) detectors.]

I. INTRODUCTION

Heavy ion (HI) reactions of the sort (HI, $xn\gamma$) (x an integer) have contributed a great deal of information on high angular momentum states in heavy nuclei. By suitable choice of bombarding energy it is possible to populate preferentially a particular final nucleus and to achieve rather clean spectra. Extending these heavy ion reactions to lighter mass nuclei is somewhat more complicated because the ($xn\gamma$) exit channel in general is no longer predominant, but as a result of the lower Coulomb barrier exit channels such as ($pn\gamma$), ($2pn\gamma$), ($\alpha p\gamma$), etc., are preferred because they lead to nuclei closer to the line of stability. Nevertheless, it is found that in the mass region near $A = 40$ relatively few γ transitions in a particular final nucleus are observed in these reactions[1-4], with the inference that these γ transitions are between the members of the yrast states. We have used the ^{32}S(^{14}N, $pn\gamma$)^{44}Ti reaction to look for high spin states in ^{44}Ti which could be associated with the rotational bands observed at low energy.[5] Recently, the study of ^{44}Ti by the reaction ^{28}Si(^{19}F, $p2n\gamma$)^{44}Ti has been reported[4] with results very similar to the present ones. However, levels in ^{44}Ti are fed somewhat differently in the two reactions, and thus each can be exploited to learn different things about the final states.

II. EXPERIMENTAL METHOD

Targets of natural CdS have been bombarded by ^{14}N beams of energies from 26 to 43 MeV using tandem accelerators at the Max-Planck-Institut, Heidelberg, and McMaster University. The reaction γ rays have been detected using large volume high resolution (~2 keV) Ge(Li) detectors. Excitation functions, Doppler shifts, and angular distributions have been measured in singles. Further details will be given in the results sections.

In order to identify the γ rays from ^{44}Ti, γ-γ coincidences between two Ge(Li) detectors, each at 90° to the beam, using address recording of the parameters of the coincident events, have been measured at a bombarding energy of 33 MeV with a resolving time of ~30 ns. A 1.5-mg/cm^2 target of CdS on a bismuth backing was used.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. γ-γ coincidences

Figure 1 shows the sum of three coincidence spectra gated by the 1083-, the 1371-, and the

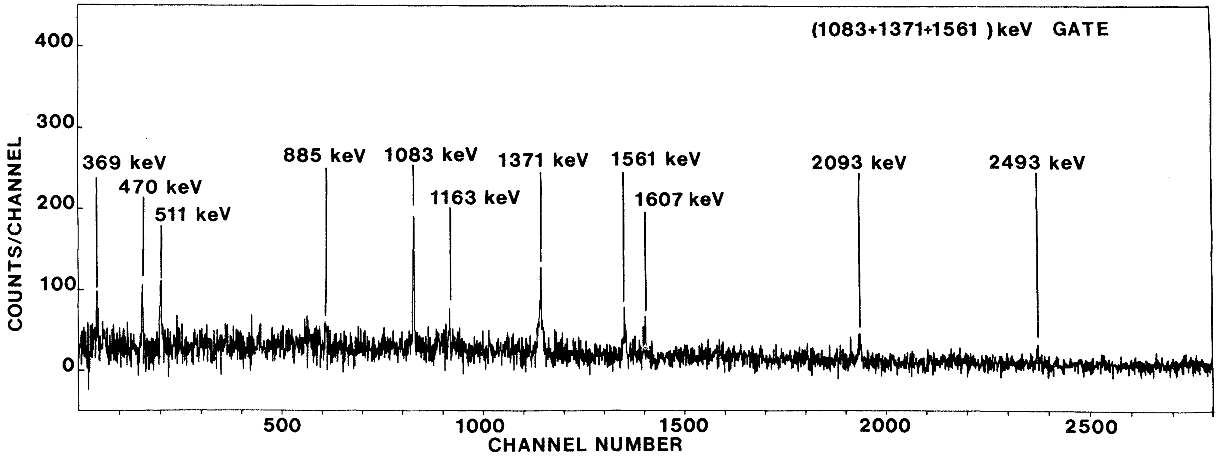

FIG. 1. γ-γ coincidence spectrum. This is a sum of spectra obtained with digital gates set on the 1083-, 1371-, and 1561-keV γ rays. Real coincidences with Compton events underlying the γ rays in the gates have been determined by setting gates just above those indicated and have been subtracted off.

1561-keV γ rays in ^{44}Ti. In this spectrum (and all other γ-γ coincidence spectra obtained) real coincidences with the background have been subtracted by setting a window near the gating peak. Random coincidence spectra were also generated for some cases, but the number of randoms in the peaks of interest were insignificant. The locations in ^{44}Ti of the γ-ray transitions identified in this figure are shown in Fig. 2. An interesting feature is evident—the γ rays seen belong to only two of the four low-energy rotational bands previously identified in α-capture experiments[5]: the ground state band and the negative parity band. The three new γ rays reported in Ref. 4 are seen, with energies of 2493, 1163, and 369 keV. Windows set on higher transitions in the ground state band indicate that these transitions feed that band, and gates set on the 369- and 2493-keV γ rays confirm the work of Kolata, Olness, and Warburton[4] that these three new γ rays are in cascade (see Fig. 2). Table I presents the energies of all the observed γ rays and their intensities when gated by other lines, corrected for the efficiency of the detectors. The coincidence data also confirm the γ-decay characteristics of the ground state and negative parity bands already elucidated in the ^{40}Ca(α, γ)^{44}Ti reaction. The data do not suggest any higher levels which could be associated with the negative parity band.

B. Excitation functions

Figure 3 shows the excitation function for the individual γ rays of the ground state band taken with 0.5-mg/cm^2 and 0.8-mg/cm^2 targets of CdS on gold backings. The Ge(Li) detector was at 90° to the beam to minimize Doppler effects. The intensity of each γ ray has been corrected for detector efficiency. The points are plotted at an effective bombarding energy which is the incident energy less one-half the energy loss in the target. One notices from this figure that there is appreciable side feeding into practically all levels at low bombarding energies, but at the higher energies the yields of many of the γ rays are nearly the

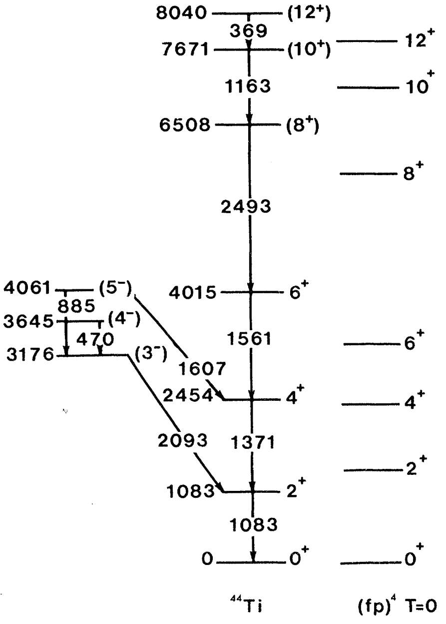

FIG. 2. Proposed decay scheme of the ground state and negative parity band (Ref. 5) of ^{44}Ti seen in the ^{32}S-(^{14}N,$p n \gamma$)^{44}Ti reaction. All energies are in keV. Also shown are the yrast levels of a full $(fp)^4$ calculation which we carried out (see Ref. 8).

TABLE I. γ-ray energies and coincidence intensities in ^{44}Ti (corrected for detector efficiencies).

Observed γ ray (keV)	Transition $J_i \rightarrow J_f$	Gating γ ray 369 keV	2493 keV	1561 keV	1371 keV	1083 keV	2093 keV
1082.9± 0.1[a]	2 → 0	51± 14	221± 30	600± 120	2070± 180	b	1380± 180
1371.4± 0.5	4 → 2	67± 16	135± 37	580± 270	b	2040± 340	
1560.7± 0.4	6 → 4	69± 18	230± 51	b	640± 400	570± 420	
2492.6± 1.4	(8) → 6	95± 16	b	460± 360	350± 260	270± 200	
1162.8± 0.3	(10) → (8)	63± 13	132± 32	240± 90	100± 150	100± 130	
368.9± 0.1	(12) →(10)	b	110± 24	77± 70	130± 60	90± 40	
2092.9± 0.8[a]	(3^-) → 2					990± 180	b
469.6± 0.1	(4^-) → (3^-)					240± 40	660± 110
1607.0± 0.5	(5^-) → 4				200± 330	490± 250	
884.7± 0.3	(5^-) → (3^-)					320± 110	390± 150

[a] Used for calibration.

[b] Gating γ ray.

same, suggesting that cascade feeding from the highest level is most important. In the ^{28}Si-(^{19}F, $p2n\gamma$)^{44}Ti reaction Kolata *et al.*[4] report that most members of the band are almost solely fed from the highest level. A digression on this point is perhaps warranted here. In an interesting letter Klapdor *et al.*[6] indicated an approximate way by which one might select a compound-nucleus reaction which would feed preferentially high spin states in the final nucleus. The method depends primarily on the angular momentum conditions in the entrance and exit channel of interest. Because the formation cross section is proportional to $2l+1$, where l is the orbital angular momentum, it is expected that the reaction cross section will peak near the grazing angular momentum (c.m.

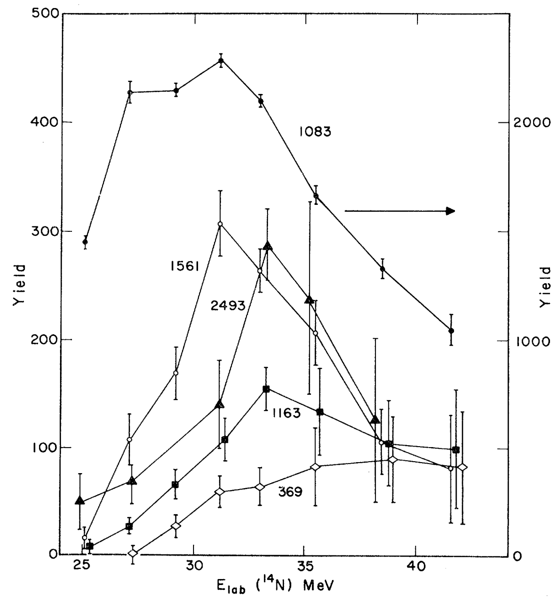

FIG. 3. Excitation function of γ rays in the ground state band of ^{44}Ti versus the effective incident energy (see text). The 1371-keV ($4^+ \rightarrow 2^+$) γ ray is not shown because of difficulties in disentangling it from the background 1368-keV γ ray of ^{24}Mg. The right hand ordinate scale applies to the curve labeled 1083.

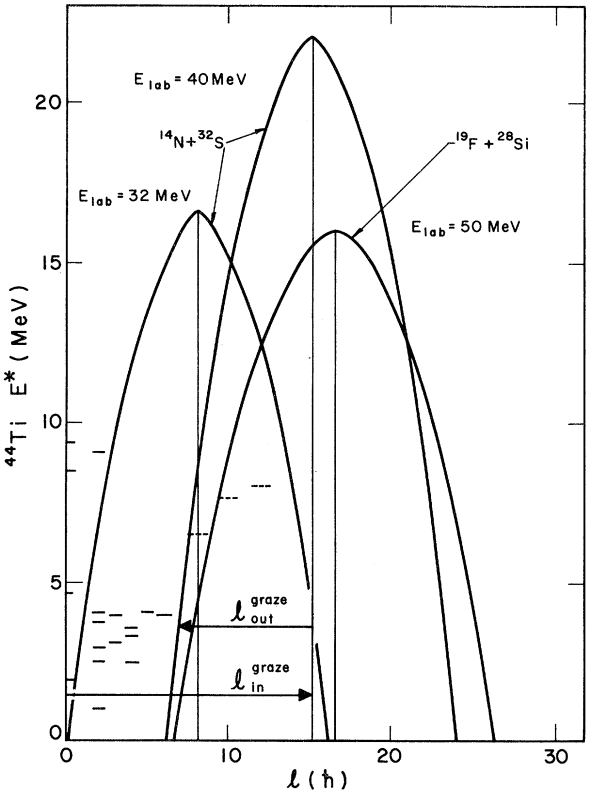

FIG. 4. Contours of grazing angular momenta of incident and exit channel. The short solid horizontal lines are known energy levels in ^{44}Ti, while the dashed ones are the newly proposed yrast states (Ref. 4 and present work).

system)

$$(l_{\text{in}}^{\text{graze}}+\tfrac{1}{2})\sim 0.22 r_{\text{graze}}[\mu(E_{\text{c.m.}}-V)]^{1/2} \quad (l^{\text{graze}}\gg 1),$$

where r_{graze} was taken to be[6] $0.5+1.36(A_1^{1/3}+A_2^{1/3})$ fm, μ is the reduced mass in amu in the entrance channel, $E_{\text{c.m.}}$ is the energy available in the center of mass, and V is the Coulomb energy at r_{graze}, both the latter in MeV. An outgoing particle to a particular final state can carry away a maximum angular momentum determined by its grazing distance from the center of mass, and for a two-body final state

$$(l_{\text{out}}^{\text{graze}}+\tfrac{1}{2})\sim 0.22 r_{\text{graze}}[\mu(E_{\text{c.m.}}+Q-E^{*}-V)]^{1/2},$$

where Q is the Q value for the complete reaction, E^* is the final state excitation energy in the residual nucleus (in MeV), and μ, r_{graze}, and V are calculated for the exit channel. The contour defined by these angular momenta is displayed in Fig. 4, and it might be expected that only final states within the contour would be appreciably excited. Klapdor *et al.*[6] show that Hauser-Feshbach calculations bear out this simple idea reasonably well. A comparison of the ^{32}S(^{14}N, $pn\gamma$)^{44}Ti and the ^{28}Si(^{19}F, $p2n\gamma$)^{44}Ti reactions seems to confirm these ideas. In Fig. 4 (where the contours have been calculated assuming a two-body final state, rather than three- and four-body) one sees that the ^{14}N-induced reaction is expected to be relatively nonselective at low energy, being able to feed even the lowest-lying states, but that at higher energies (say 40 MeV) it becomes more selective, predominantly feeding the higher states, and qualitatively this is what is observed, as seen in Fig. 3. The ^{19}F-induced reaction is expected to be highly selective, feeding only the highest spin states, and qualitatively this too is what is observed.[4] These ideas can also be used to indicate the predominant competing reactions. For example, the ^{32}S(^{14}N, $2p\gamma$)^{44}Sc reaction would be expected to be roughly as strong as that leading to ^{44}Ti, and indeed there are three γ rays seen, of 696, 895, and 1703 keV, which are attributed[4] to cascades in ^{44}Sc and the lowest member of the cascade, the 696-keV γ ray, has an intensity equal to that of the 1083-keV γ ray in ^{44}Ti at a bombarding energy of ~32 MeV. Thus the simple grazing-collision idea of Klapdor *et al.*[6] is useful for choosing reactions which feed particular final states. An advantage of the ^{14}N-induced reaction over the ^{19}F-induced reaction of Ref. 4 is that the appreciable side feeding allows the unambiguous determination of the order of γ rays in the cascade (Fig. 2).

The excitation functions of the γ rays in the negative parity band are similar to those of the ground state band. At 32 MeV, approximately 40% of the 1083-keV γ ray is accounted for by feeding from the 3^- state via the 2093-keV γ ray.

C. Angular distributions

Table II presents the angular distribution coefficients for some of the γ rays measured at a bombarding energy of 36 MeV. Because of the appreciable Doppler broadening of many of the γ rays (arising because of the side feeding into the levels) and proximity to background lines, it was not possible to obtain angular distributions for all γ rays. The coefficients are in reasonable agreement with stretched transitions considering the appreciable dealignment resulting from the cascading and experimental uncertainties.

D. Doppler-shift lifetime measurement

Because of the appreciable side feeding we were able to observe a Doppler broadening on the 1163-keV γ ray, the presumed $10^+ \to 8^+$ transition. A

TABLE II. Angular distribution coefficients for γ rays produced in the ^{32}S(^{14}N,$pn\gamma$)^{44}Ti reaction.

E_γ (keV)	$J_i^\pi \to J_f^\pi$	a_2	a_4	α_2 [a]	Multipolarity
1083	$2^+ \to 0^+$	0.16 ± 0.04	-0.07 ± 0.04	0.22	$E2$
1163	$(10^+) \to (8^+)$	0.54 ± 0.13	-0.41 ± 0.17	~1.0	($E2$)
369	$(12^+) \to (10^+)$	0.22 ± 0.11	0.02 ± 0.14	0.55	($E2$)
2093	$(3^-) \to 2^+$	-0.15 ± 0.03	-0.03 ± 0.04	0.38	($E1$)
		-0.16 ± 0.02	···	0.40	
470	$(4^-) \to (3^-)$	-0.12 ± 0.02	0.07 ± 0.03	0.34	($M1$)[b]
		-0.09 ± 0.03	···	0.25	

[a] Ratio of experimental to theoretical a_2 for transitions from completely aligned states.

[b] The values of a_2 and a_4 are also consistent with a large δ ($\delta \sim 4$–7) which agrees with α-capture work [W. R. Dixon, R. S. Storey, and J. J. Simpson (unpublished)] but would not be consistent with the lifetime of the (4^-) state reported in Ref. 4.

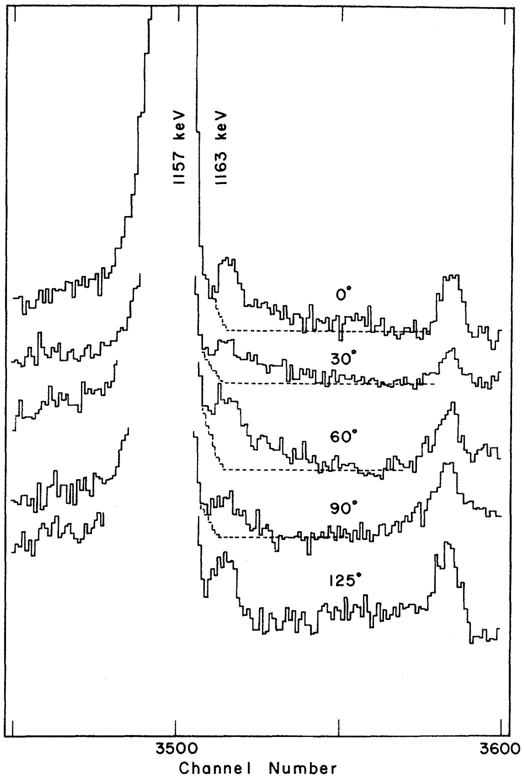

FIG. 5. Lineshape of the 1163-keV γ ray in ^{44}Ti as a function of the angle of the γ-ray detector. The 1157-keV γ ray is an activity line from the decay of ^{44}Sc to the ^{44}Ca first excited state. The dashed lines indicate the background used in the centroid determinations.

^{14}N beam of 36-MeV energy bombarded a 2.8-mg/cm^2 target of CdS on a gold backing at 45° to the beam direction. Figure 5 shows the 1163-keV γ ray as a function of angle, and Fig. 6 shows the centroid shifts as a function of $\cos\theta$. The shape of the background under the peak, as indicated in Fig. 5, was taken primarily from the background observed at 90° and 125°. The background on the low side was determined by fitting the 1157-keV activity γ-ray lineshape with the shape of the 1083-keV γ ray. The expected full shift (0°–90°) of 23 keV was determined from the observation of a fully shifted peak for the 2493-keV γ ray of the $6.51\rightarrow 4.02$ MeV transition (see Table III), and is consistent with the kinematics. It is clear that the centroids obtained at 0° and 30° are particularly sensitive to the background and this results in large errors for these points as shown in Fig. 6. The experimentally observed $F(\tau)$ is 0.131 ± 0.012. However, the 7.67-MeV level is also fed by the 369-keV γ ray from the long-lived[4] 8.04-MeV level. The yield of the 369-keV γ ray was also obtained during the lifetime measurement and was determined to be $(27\pm 4)\%$ consistently at all angles. The $F(\tau)$ value of the 1163-keV transition corrected for the 369-keV feeding is 0.18 ± 0.02. This as-

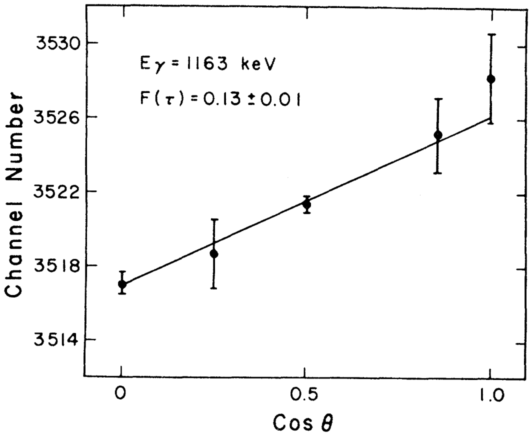

FIG. 6. Centroid of the 1163-keV γ ray as a function of the cosine of the γ-ray detector angle. The point at θ of 75° was determined with different electronic gain and is not shown in Fig. 5. The line is a least-squares fit to the points.

TABLE III. Lifetimes and $B(E2)$ values in ^{44}Ti.

E_i (keV)	E_f (keV)	J_i	J_f	τ_i (ps)	Reference	$\lvert M(E2)\rvert^2$ (W.u.)	$B(E2; J_i\rightarrow J_f)$ e^2fm^4 Experiment	$(fp)^4$ model	Rot. model [a]
1082.9 ± 0.1	0	2	0	$4.5\ \pm 1.1$	7	13 ± 4	120 ± 30	121	102
2454.3 ± 0.5	1083	4	2	$0.6\ \pm 0.1$	7	30 ± 6	280 ± 60	166	146
4015.0 ± 0.6	2454	6	4	0.56 ± 0.08	5	17 ± 3	160 ± 20	138	160
6507.7 ± 1.5	4015	(8)	6	<0.7[b]	This work	>1.5	>14	104	168
7670.5 ± 1.5	6508	(10)	(8)	$2.7\ \pm 0.5$	This work	15 ± 3	140 ± 30	104	173
8039.5 ± 1.5	7671	(12)	(10)	>2000	4	<6.5	<60	55	176

[a] Least squares fit to the four experimentally measured values.

[b] Estimated from observation of a fully shifted peak, implying $F(\tau) > 0.5$.

sumes all other feeding to be prompt. Using an excitation function-weighted $F(\tau)$ calculated using the Lindhard stopping power theory, the lifetime determined for the 7.67-MeV state is 2.7 ± 0.5 ps. Table III presents lifetimes, $B(E2)$ values, and $E2$ enhancements in Weisskopf units (W.u.) for the ground state band of ^{44}Ti. For comparison, we have made calculations of an $(fp)^4$ shell model and the symmetric rotor model. The shell model calculations (outlined in Ref. 8) use a constant effective charge of 0.5 added to the bare proton and neutron charges. The shell model energy levels are also shown in Fig. 2. One sees that the experimental $E2$ transition strengths are in agreement with both models except for the $12^+ \rightarrow 10^+$ transition, where the agreement is much better with the shell model. It is noted that the shell model predicts the energies of the higher spin states also reasonably well, although the spacing among the lower states is not very good. In fact, as Kolata *et al.* show in their paper,[4] the calculations[9] of McCullen, Bayman, and Zamick, which confine the four valence nucleons to the $f_{7/2}$ shell and use an effective interaction taken from ^{42}Sc, is better able to reproduce the energy levels of the yrast band, although not the reduced $E2$ transition strengths.

IV. CONCLUSIONS

In the study of the reaction ^{32}S(^{14}N, $pn\gamma$)^{44}Ti a number of interesting features have emerged. It has been found that the reaction predominantly feeds only the ground state band and the negative parity band in ^{44}Ti and the same γ rays are seen in the ^{28}Si(^{19}F,$p2n\gamma$)^{44}Ti reaction. It is also observed that the ^{14}N-induced reaction at low energies has significant side feeding into all states, whereas the ^{19}F reaction and the ^{14}N reaction at higher energies feed predominantly the highest lying level. Following a suggestion by Klapdor *et al.*, a simple method for suggesting which levels might be fed in heavy ion reactions has been proposed. The ^{14}N-induced reaction selectively populates what appears to be a unique set of levels of the "ground state" band, including the known 2^+, 4^+, and 6^+ members. An additional three γ rays are seen feeding in cascade the 6^+ state, and they are interpreted as transitions between levels at 6508, 7671, and 8040 keV.[10] The decay properties of these levels, such as angular distributions and absence of crossover transitions, are consistent with the suggested 8^+, 10^+, and 12^+ sequence. By observation of the attenuated Doppler shift, the lifetime of the (10^+) state has been determined and indicates a relatively enhanced transition to the (8^+) state.

With regard to the structure of ^{44}Ti, it appears that the higher lying members of the ground state band are perhaps rather well explained by the shell model if the postulated levels and J^π are correct, whereas it has been shown that the three positive parity bands in the low energy part of the spectrum (up to ~4 MeV) can also be very well accounted for by a soft asymmetric rotor picture.[5,11] This dichotomy of structure remains an unsatisfactorily explained feature of many nuclei in the lower (fp) shell.

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